# Main Injector/NuMI BPM Scaling

# Analysis of Main Injector HP602 and HP604 BPM Data from Traditional Main Injector and NuMI BPM Systems

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## Introduction

The NuMI BPM system requires measurements from four BPMs in the Main Injector ring as well as down the NuMI beam line. Four Main Injector BPMs, horizontal 602, 604 and 606, and vertical 605, are now instrumented with both the traditional AM-PM processing system and Echotek digital receivers. Power splitters in the service building provide signals from the Main Injector style BPM pick-ups to the two different electronics systems. Data from both systems was acquired on August 13, 2004, by Vickie Frohne, Alberto Marchionni, Peter Prieto, and Phil Schreiner in an effort to check and compare calibration of the two systems. Local horizontal beam bumps were used to move the beam at the horizontal 602 and 604 locations. This note is an analysis of that data.

## Measurement Data

Tables 1 and 2 contain the original measurement data. The Scale Factor column data represents the strength of the local magnetic position bump, the I:HP60x column data is the reported beam position from the standard Main Injector BPM system and E:HP60x[n] column data is reported beam position for batches 1 and 4 from the NuMI system. All beam position data is in units of millimeters.

Table 1 Data from location HP602

| Scale factor 602 bump | I:HP602 | E:HP602[1] | E:HP602[4] |
|---|---|---|---|
| -12 | 11.13 | 17.03 | 17.04 |
| -8.996 | 7.671 | 13.43 | 13.52 |
| -5.996 | 5.499 | 9.245 | 9.295 |
| -3.004 | 3.005 | 4.69 | 4.67 |
| 0 | 0.3466 | 0.16 | 0.11 |
| 1.66 | -1.0298 | -2.81 | -2.8 |
| 3 | -2.217 | -4.67 | -4.65 |
| 5.004 | -3.83 | -8 | -8 |
| 7.004 | -5.366 | -10.955 | -10.94 |
| 9.004 | -7.01 | -13.645 | -13.425 |
| 11 | -8.841 | -16.125 | -16.145 |
| 13 | -10.69 | -18.385 | -18.385 |
| 15 | -12.68 | -20.34 | -20.37 |
| 17 | -14.47 | -22.08 | -22.13 |
| 19 | -16.54 | -23.575 | -23.63 |

Table 2   Data from location HP604

| Scale factor 604 bump | I:HP604 | E:HP604[1] | E:HP604[4] |
|---|---|---|---|
| -9.004 | 17 | 21.8 | 21.6 |
| -8.5 | 15.74 | 21 | 20.8 |
| -8 | 14.68 | 20.1 | 19.9 |
| -7 | 12.58 | 18.4 | 18.2 |
| -6.391 | 11.46 | 17.2 | 17 |
| -5.578 | 10.09 | 15.6 | 15.4 |
| -3.574 | 6.733 | 10.8 | 10.6 |
| -1.563 | 3.647 | 5.36 | 5.23 |
| 0 | 1.236 | 0.955 | 0.861 |
| 1.777 | -1.523 | -4.1 | -4.16 |
| 3.512 | -4.069 | -8.75 | -8.78 |
| 4.754 | -5.822 | -11.9 | -11.9 |

## Initial Correlation of Positions Reported by the Two Systems

Figures 1 and 2 respectively show the correlation between reported positions from the two systems at locations HP602 and HP604. Each plot also displays a linear fit of the relationship for points between plus and minus 7 mm as reported by the Main Ring system. Two discrepancies between the systems are apparent. The position scaling gain of the NuMI system is high by a factor of about 1.8 and there are large non-linear differences.

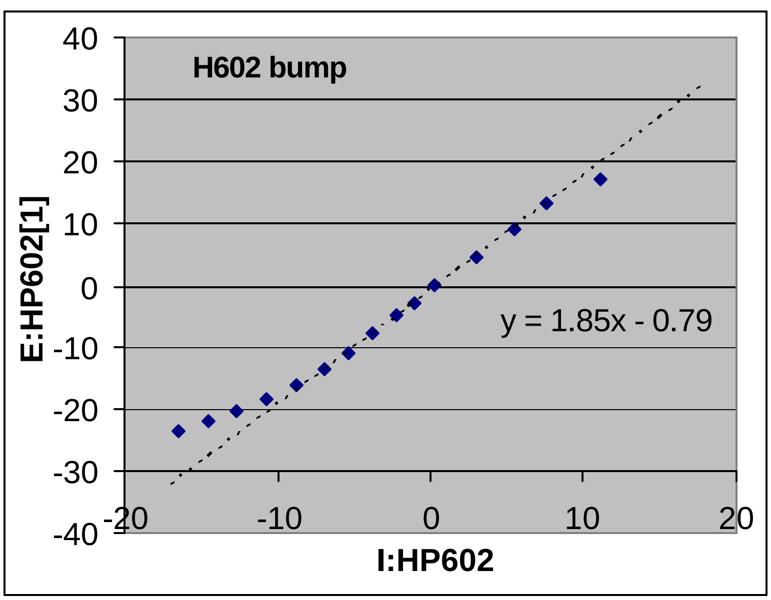


Figure 1   Initial correlation between HP602 reported positions

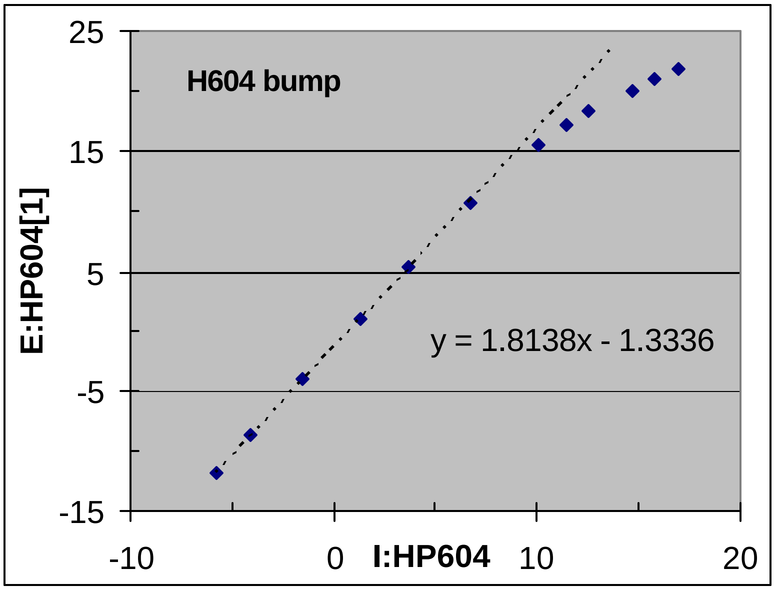

Figure 2 Initial correlation between HP604 reported positions

## Improvements to the NuMI System Algorithm

The NuMI system was using a simple linear scaling transformation to compute position from the magnitude of the two BPM signals as processed by the Echotek board. The scaling gain discrepancy with respect to the MI BPM system suggested that an incorrect value had been used. Investigation determined that indeed to be the case. A BPM sensitivity number of 0.48 db/mm contained in a document provided by Jim Crisp had been incorrectly understood and applied. The corresponding (and correct) linear factor actually used in the Main Injector system is 0.90 db/mm. That ratio of 1.875 is consistent with the linear scaling difference between the two systems.

To get a handle on the non-linear differences, the complete transformation used in the Main Injector system needs to be considered. That system uses a 5$^{th}$ order polynomial to compute position from the digitized value of the BPM RF Module output voltage. That function for the different Main Injector BPMs is identified in Jim Crisp's document as:

$$Pos[mm] = C_1 * V^5 + C_3 * V^3 + C_5 * V + C_6 \qquad (1)$$

| | pos from Vrfmod | | |
|---|---|---|---|
| | H MI bpm | V MI bpm | wide bpm |
| C1 | .232 | .297 | .258 |
| C3 | .153 | .673 | .571 |
| C5 | 5.839 | 8.462 | 13.248 |
| mm range | 27.5/-26.9 | 42.7/-41.7 | 50.0/-49.1 |

This transform includes the combined non-linearity of the BPM pick-up response and the BPM RF Module AM-PM processing transfer function.

The RF Module transfer function is documented in Tevatron BPM Design Note #1 by Bob Shafer, refined by Don Martin in Tevatron BPM Design Note #4, and referenced in Greg Vogel's Main Injector Note #0226A. The RF Module transfer function is:

$$(A/B)_{db} = \frac{-20}{F * \ln(10)} * \ln[\tan(F * C_1 * (V - V_0) + \frac{p}{4})] \qquad (2)$$

where $(A/B)_{db}$ is the ratio of the two electrode signal amplitudes in decibels, and $F$ is Martin's empirical fudge factor, $C_1$ is the AM-PM scale factor (different from the $C_1$ from in Equation 1), $V$ is the RF Module position signal output voltage, and $V_0$ is an offset voltage. The accepted parameter values and those used in the Main Injector system are $F$ = 1.14, $C_1$ = 0.2974, and $V_0$ = 0.0.

The inverse relation with numerical parameter values substituted is:

$$V = -2.3168 + 2.9499 * \tan^{-1}[\exp((A/B_{db})/-7.6192)] \qquad (3)$$

Unlike the AM-PM RF module, the NuMI signal processing electronics produces individual, linearly scaled numerical values representing the measured amplitudes of each input signal. Computation of beam position from those values requires a suitable description of the Main Injector BPM pick-up transfer function separately from that of the RF Module. With no document defining that function readily available, Equations 1 and 3 were used to derive a numerical representation. The result for a horizontal BPM is:

$$(A/B)_{db} = -0.919 * x + 5.1657 * 10^{-4} * x^3 - 7.5538 * 10^{-7} * x^5 \qquad (4)$$

and inversely,

$$x = -1.0835 * (A/B)_{db} - 9.5487 * 10^{-4} * (A/B)_{db}^{\ 3} + 1.9119 * 10^{-6} * (A/B)_{db}^{\ 5} \qquad (5)$$

where x is the beam position in millimeters.

These relations were checked against wire measurement data of one MI BPM and found to agree to within 0.1 db, about 0.1 mm, out to plus or minus 18 mm. At 20 mm the error was nearly 1 db and increasing very rapidly. This is shown in Figure 3. Since all data under consideration herein are at positions within 18 mm, this representation is taken as satisfactory for present purposes. Additional consideration should be given before applying these relations more generally.

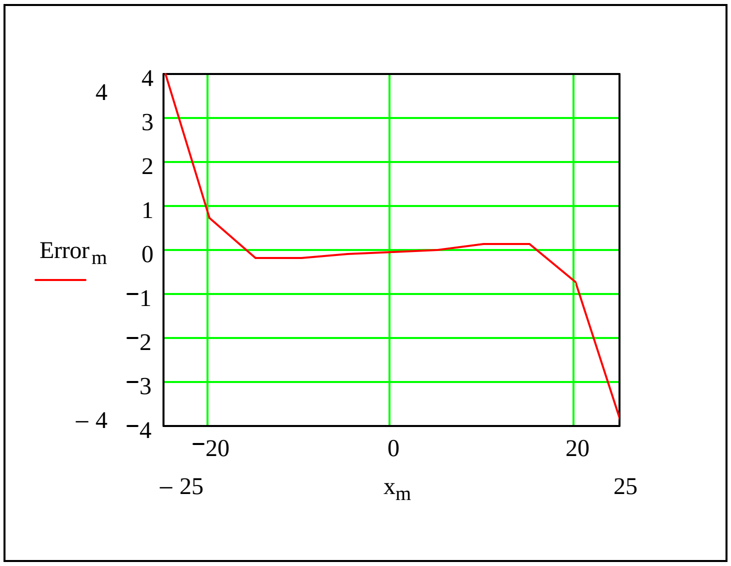


Figure 3 Difference between $(A/B)_{db}$ vs. position (mm) for the numerically derived BPM transfer function and measurement data from one randomly selected MI BPM.

The position algorithm in the NuMI system when the data was obtained was:

$$pos[mm] = R_{eff} * \left(\frac{A-B}{A+B}\right) \qquad (6)$$

where $R_{eff}$ = 36.55 mm is the effective BPM radius scale factor and $A$ and $B$ are the BPM signal amplitudes reported by the digital receiver electronics.

Using Equations 4 and 6 and the relationship between $(A/B)_{db}$ and difference over sum BPM signal representations:

$$(A/B)_{db} = \frac{40}{\ln(10)} * \left[\frac{A-B}{A+B} + \frac{1}{3} * \left(\frac{\mathrm{A - B}}{\mathrm{A + B}}\right)^3 + \frac{1}{5} * \left(\frac{A-B}{A+B}\right)^5 + \ldots\right] \qquad (7)$$

the recorded NuMI data can be corrected with a proper linear scale factor and reasonable approximation of the BPM transfer function non-linearities.

The results, shown in Figures 4 and 5, are to be compared to the un-corrected data shown in Figures 1 and 2. A straight-line fit over the full position range finds the slopes of the corrected data correlations are 0.967 and 0.915 for HP602 and 604 respectively with the 604 fit skewed low by a visible asymmetry in the acquired data. This is considerably better agreement than with the un-corrected data. To within a constant offset, the corrected NuMI system data agrees at both locations with positions reported by the MI system to better than 1 mm for all data out to ±15 mm.

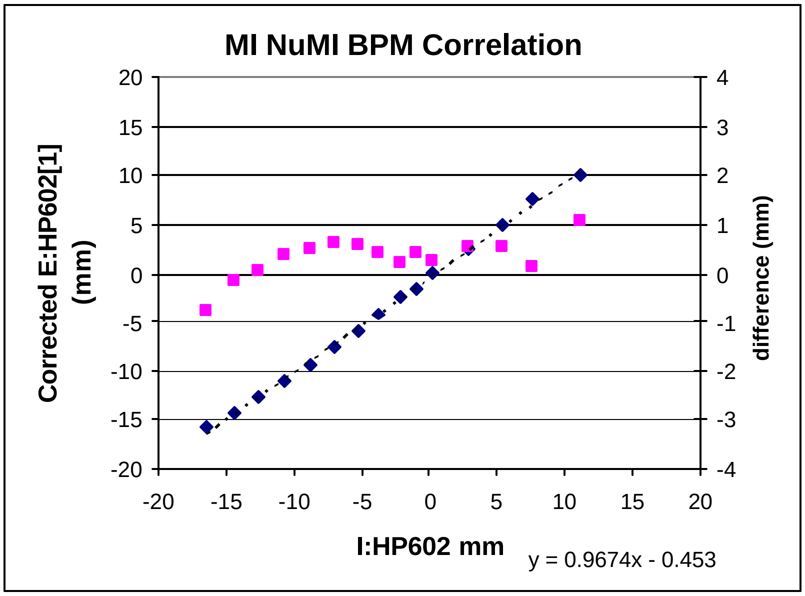


Figure 4 Correlation and differences between HP602 reported positions from the two systems using corrected NuMI system data

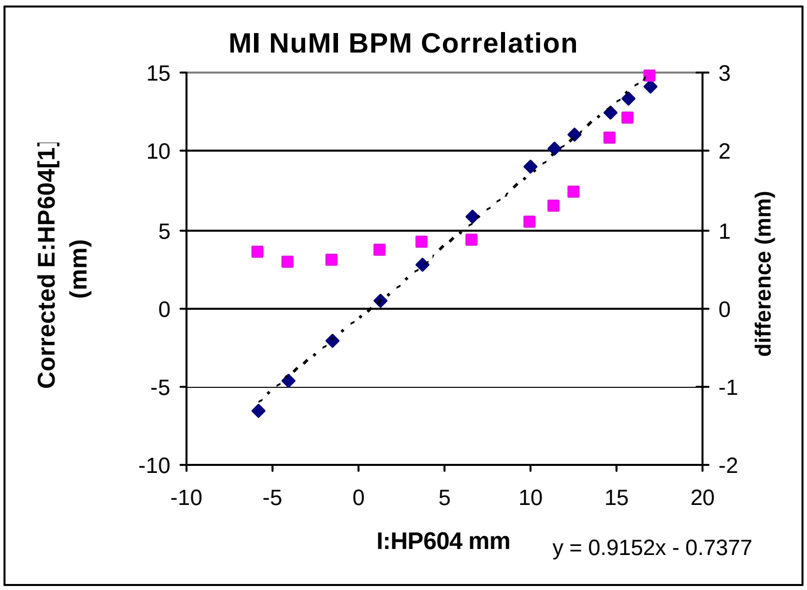


Figure 5 Correlation and differences between HP604 reported positions from the two systems using corrected NuMI system data

## An Independent Linearity Check

The residual differences between MI system and corrected NuMI system data exhibit a strong non-linear character. The position bump magnet scale factors included in the recorded data allow testing the linearity of reported positions with bump current.

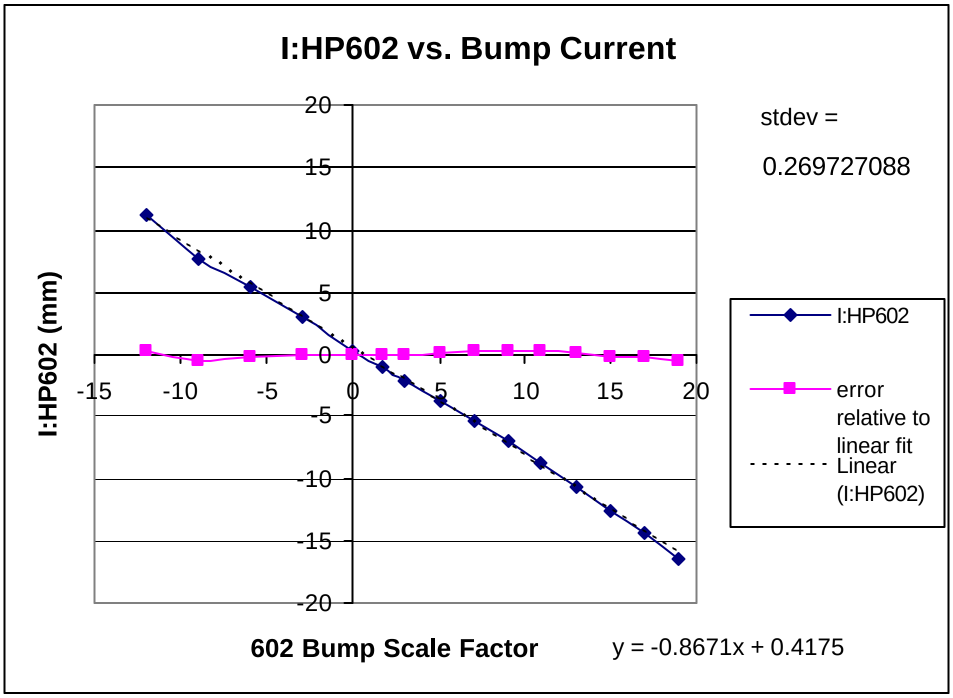


Figure 6 MI system reported HP602 positions as function of 602 Bump Scale Factor and difference from straight-line fit.

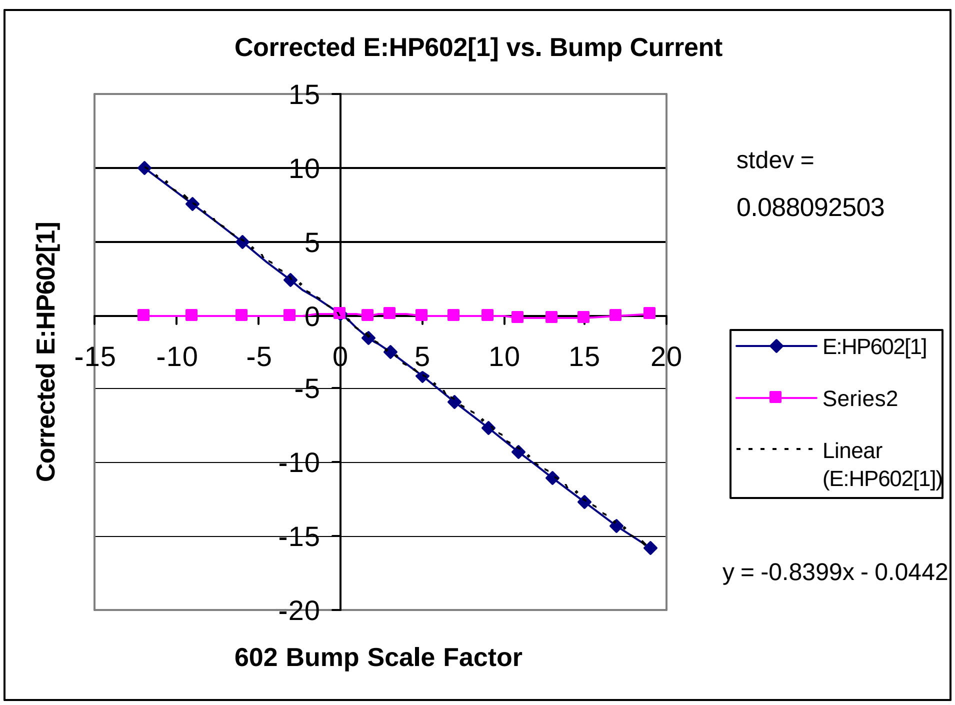


Figure 7 NuMI system corrected HP602 positions as function of 602 Bump Scale Factor and difference from straight-line fit.

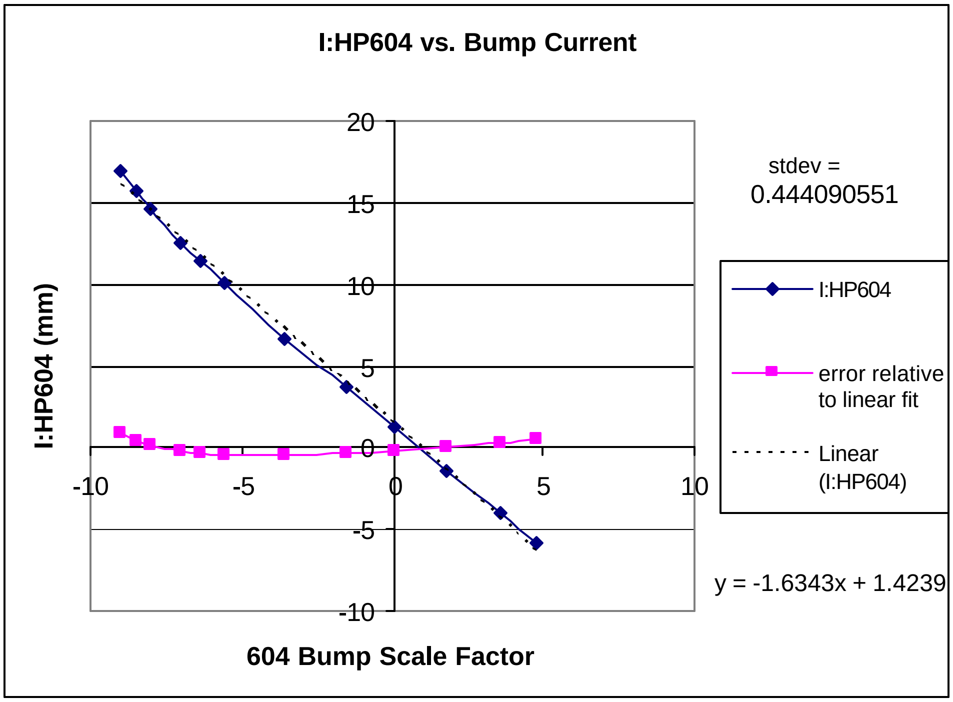


Figure 8 MI system reported HP604 positions as function of 604 Bump Scale Factor and difference from straight-line fit.

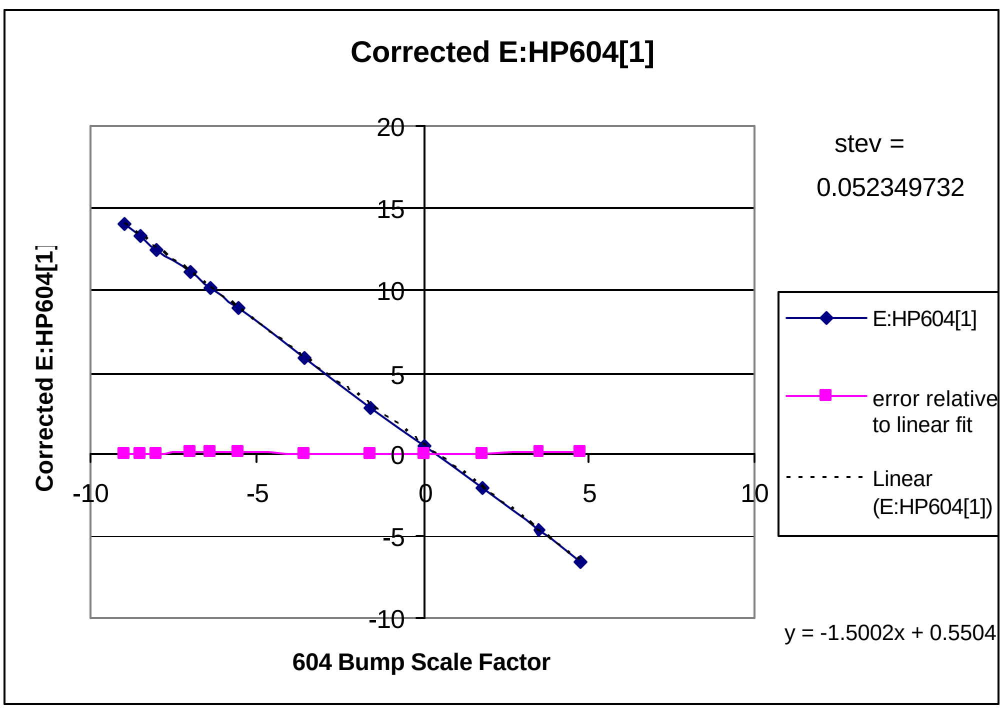


Figure 9 NuMI system corrected HP604 positions as function of 604 Bump Scale Factor and difference from straight-line fit.

The reported (corrected in the case of NuMI) beam position versus bump scale factor for the two systems at the each location is plotted in Figures 6-9. The figures include linear fits of the data, plots of the difference between measurements and the linear fit, and the standard deviation of the differences. Using the standard deviation value as a figure of merit, the linearity between bump amplitude and reported position is best for the corrected NuMI HP604 data (stdev = 0.052) and worst for the MI HP604 data (stdev = 0.444). The HP602 data similarly indicate better agreement for corrected NuMI data (stdev = 0.088) than MI data (stdev = 0.270). Assuming that the bump scale factors accurately represent the bump magnet current and a linear relationship between magnet current and beam position, these data suggest that the corrected NuMI data might in fact better represent beam position than MI system data.

## Summary

Data was taken to compare beam position measurements reported by the Main Injector and NuMI style BPM systems in the Main Injector with Main Injector BPM pick-ups. It was found that a linear scaling between position and a difference over sum representation of MI style BPM pick-up signals is unsatisfactory. A non-linear relationship was found that produces agreement between the systems to better than 1 mm for positions out to ±15 mm. The corrected NuMI system data show a relationship with 3-bump magnet current that is more linear than the data MI BPM system data.